



SECOND EDITION

POWER SYSTEMS ANALYSIS

**ARTHUR R. BERGEN
VIJAY VITTAL**

Power Systems Analysis

Second Edition

ARTHUR R. BERGEN

*Department of Electrical Engineering
and Computer Sciences*

University of California, Berkeley

VIJAY VITTAL

*Department of Electrical
and Computer Engineering*

Iowa State University, Ames

PRENTICE HALL,
Upper Saddle River, New Jersey 07458

Library of Congress Cataloging-in-Publication Data

Bergen, Arthur R.

Power systems analysis / Arthur R. Bergen, Vijay Vittal.—2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-13-691990-1

1. Electric power systems 2. System analysis. I. Vittal, Vijay. II. Title.

TK1001.B44 2000

621.31—dc21

99-20875

CIP

Publisher: Tom Robbins

Associate Editor: Alice Dworkin

Editorial/Production Supervisor: Rose Kernan

Copy Editor: Pat Daly

Cover Designer: Bruce Kensaleer

Manufacturing Buyer: Pat Brown

Editorial Assistant: Dan DePasquale

Marketing Manager: Danny Hoyt

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Upper Saddle River, New Jersey 07458

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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-691990-1

PRENTICE-HALL INTERNATIONAL (UK) LIMITED, *London*

PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *Sydney*

PRENTICE-HALL OF CANADA, INC., *Toronto*

PRENTICE-HALL HISPANOAMERICANA, S.A., *Mexico*

PRENTICE-HALL OF INDIA PRIVATE LIMITED, *New Delhi*

PRENTICE-HALL OF JAPAN, INC., *Tokyo*

PRENTICE-HALL (SINGAPORE) PTE. LTD., *Singapore*

EDITORIA PRENTICE-HALL DO BRASIL, LTDA., *Rio de Janeiro*

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Preface

To the second edition

Much has changed since the *first edition* of this book went to press in 1986. The electric utility industry in the United States has undergone major changes in its structure and operating practices. In many parts of the country, the monopolistic and regulated vertically integrated utility system is being replaced by a (partially) deregulated multi-layered system open to competition and other market forces. The second edition includes material which reflects these changes and deals with issues related to the new environment.

In addition, a number of thoughtful suggestions by professors and students who have used the first edition have been incorporated. While continuing to stress fundamentals, there is somewhat more emphasis on industry practice and on computer applications.

The many changes in the *second edition* include the following: The chapters have been reordered to provide a more systematic development of the material. A new section on determining transmission line parameters from manufacturers' tables has been introduced in Chapter 3. In the same chapter, a more complete and accurate description of transmission line impedance parameters of transmission lines with ground returns has been provided. Chapter 9 is an entirely new chapter on the subject of network matrices. The topic of matrix factorization and its applications to matrix inversion is included. Also included is the modern approach of determining only needed elements of the impedance matrix. Chapter 10 on power flow solutions has been expanded to describe the modifications needed when practical limits are encountered. In Chapter 11, titled "Automatic Generation Control and the New Market Environment", some ideas currently being utilized for power system operation and control are introduced. Chapter 12 on unbalanced system operation and fault analysis has been substantially revised and includes new material describing industry practice.

A salient feature of the second edition is a running design problem that is first introduced in Chapter 3 and continues in each successive chapter as relevant new concepts are presented. The design problem is computer oriented; the student may use available software, or may develop software using MATLAB[®]. These design examples are involved and are ideally suited for group projects.

The material in the text has expanded to the point where it seems clear that two semesters would be required to cover the material. If this much time is not available, however, there are alternative pathways through the text. Chapters 7, 8, and 11 might be left out without seriously affecting the coherency of the remaining material. For the student with some background in energy conversion and electrical machines, Chapters 1, 2, the first part of Chapter 5, and Chapter 6 might be excluded. If pressed for time, Chapter 10 and much of the material at the ends of Chapters 11, 12, 13, and 14 could be left out without affecting continuity.

For updates, information regarding available Web sites related to power system analysis and power issues, as well as additional resources please visit our Web site at <http://www.prenhall.com/bergen/vittal>.

We would like to express our appreciation and thanks to the following reviewers for their helpful comments and suggestions: Professor Ali Abur, Texas A&M University, Professor Miroslav Begovic, Georgia Institute of Technology, Professor Brian K. Johnson, University of Idaho, and Professor Arun G. Phadke, Virginia Polytechnic Institute and State University.

There are many others whose contributions we would like to acknowledge. Among these we would particularly like to thank our colleagues Professors M. A. Pai, S. S. Venkata, G. B. Shablé, K. C. Kruempel, and J. D. McCalley for their valuable advice and comments. We would also like to recognize our students who helped in developing some of the new examples.

Finally, we would like to express our sincere thanks to Sunanda Vittal for her careful proofreading of the book.

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Background

1.0 INTRODUCTION

In this chapter we give a simplified description of a power system. The system consists of power sources, called *generating plants (or generators)*, power end users, called *loads*, and a transmission and distribution network that connects them. Most commonly the generating plants convert energy from fossil or nuclear fuels, or from falling water, into electrical energy.

1.1 ELECTRIC ENERGY

Electricity is only one of many forms of energy used in industry, homes, businesses, and transportation. It has many desirable features; it is clean (particularly at the point of use), convenient, relatively easy to transfer from point of source to point of use, and highly flexible in its use. In some cases it is an irreplaceable source of energy.

Figure 1.1 is a useful summary of electric energy sources and their transition to end uses for the United States in 1996. The basic energy sources are shown on the left. The end uses of the electricity are shown on the right. Only about one-third of the resource energy is converted into electricity; about two-thirds is lost as “waste heat.” In some cases this heat is not wasted. It can be used for heating homes and offices or for some industrial processes.

In Figure 1.1, the T & D losses are transmission and distribution losses (almost 10% of the net generation of electricity). Also, note the significant amount of non-utility energy generated in 1996. Changes in government energy policy have encouraged this growth. In the period from 1990 to 1995, nonutility power generation grew by 47%.

Figure 1.2 provides more detail regarding the major sources of utility-generated electrical energy and some trends in their relative importance. It can be seen that most of the production has been in conventional steam plants. *Conventional steam* refers to steam generation by burning coal, petroleum, or gas. In 1996 approximately 3000 billion kilowatthours of electricity were produced. Of this, coal

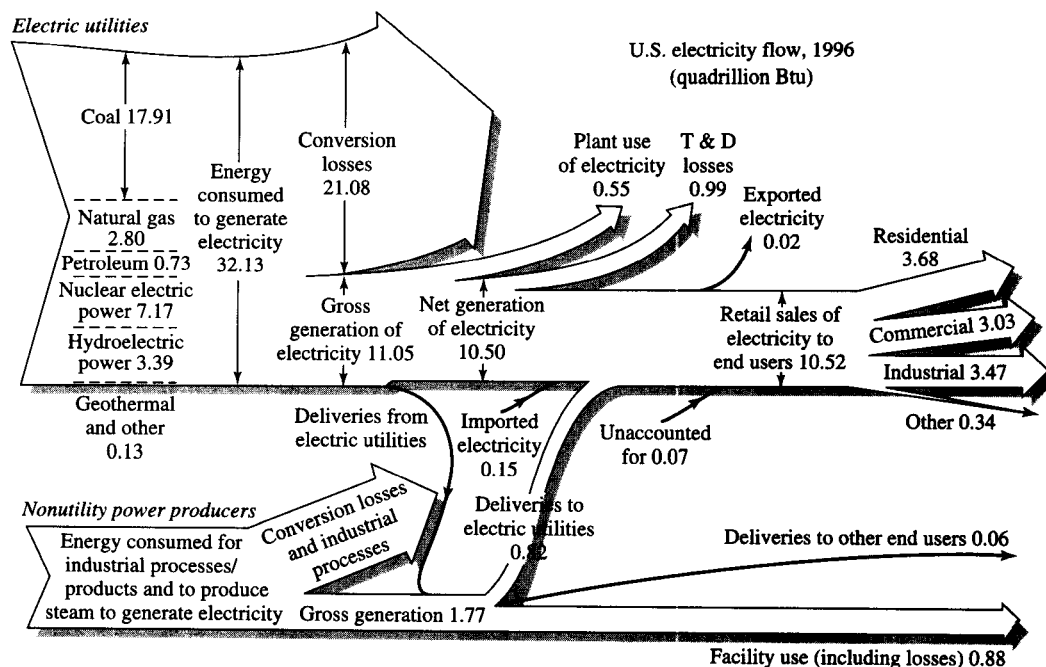


Figure 1.1 U.S. electricity supply and demand. (From *Annual Energy Review 1996*, U.S. Department of Energy.)

accounted for approximately 56%, petroleum 2%, natural gas 8% (totaling 66% for conventional steam), hydropower 11%, nuclear power 22%, and others, including gas turbines, about 2%. Note that nuclear and geothermal power plants also generate steam but not by burning fossil fuels.

The units used in Figure 1.1 are quadrillion Btu (10^{15} , or quads), while those in Figure 1.2 are in billion kilowatthours (or 10^9 watthours or gigawatthours). In attempting to align the figures, we can use the conversion factor 1 watt = 3.413 Btu/hr.

Turning to the growth in utility electricity production, we see in Figure 1.2 an almost exponential growth rate until about 1973. Until that time electricity use doubled every 10 years or so. Subsequently, the growth rate dropped, at first reflecting the general slowdown of worldwide economic growth precipitated in large part by the oil crisis of 1973 and later by an increasing awareness of the cost-effectiveness of energy conservation.

Figure 1.3 shows the growth in installed utility-generating capability in the United States. In 1996, of the total installed generating capability of approximately 710 million kilowatts, some 63% was conventional (fossil fuel) steam, 14% was hydropower, 14% was nuclear, 8% was gas turbine, and others totaled about 1%. Comparing these with the production figures given earlier, we see great differences in the utilization rates of the various sources. Nuclear power has the highest rate. Gas

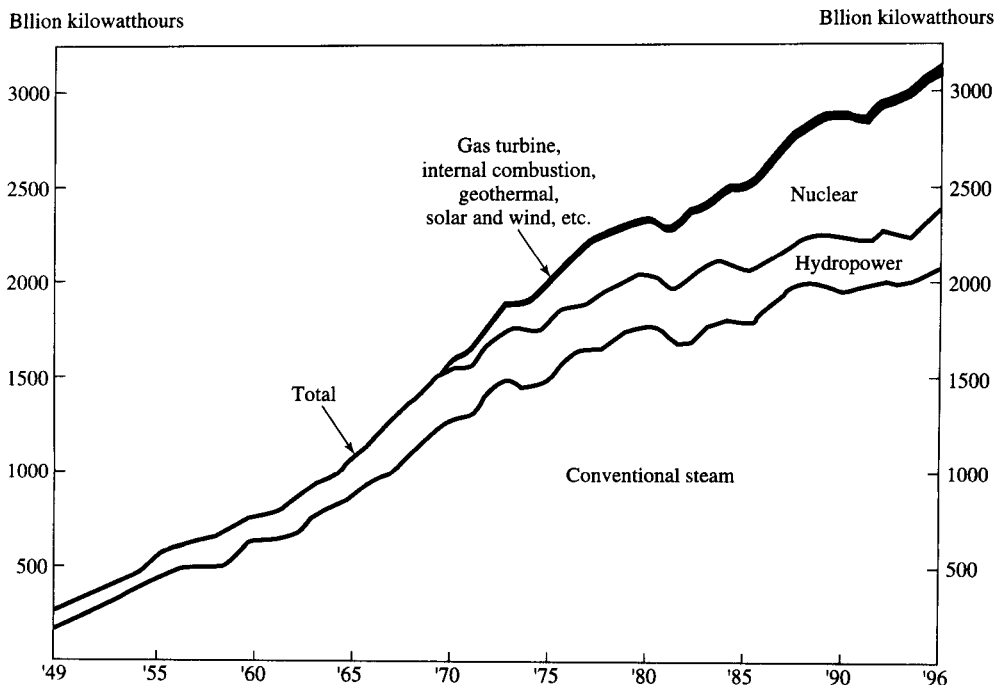


Figure 1.2 Electric utility energy production (United States). (From *Annual Energy Review 1996*, U.S. Department of Energy.)

turbines and internal combustion engines are among the lowest in the rate of utilization. We will discuss the reasons in a moment.

First, it is interesting to calculate an overall utilization factor for 1996. Suppose that it had been possible to utilize the 710 million kilowatt capability full time. Then the plants would have produced $710 \times 10^9 \times 8760 = 6220 \times 10^{12}$ watthours in 1996. They actually produced 3078×10^{12} watthours. Thus the annual capability factor or load factor was $3078/6220 = 0.49$ or 49%. Why isn't the figure higher?

There are two main reasons. The first is that generating units are not always available for service. There is downtime because of maintenance and other scheduled outages; there are also forced outages because of equipment failures. The availability of fossil-fuel steam turbine units ranges from about 80% to about 92%.

The second reason involves a characteristic of the load. While there must be enough generating capability available to meet the requirements of the peak-load demand, the load is variable, with daily, weekly, and seasonal variations, and thus has a lower average value. The daily variations are roughly cyclic with a minimum value (the *base load*) typically less than one-half of the peak value. A typical daily load curve for a utility is shown in Figure 1.4. The (weekly) capability factor for this particular utility is seen to be approximately 65%.

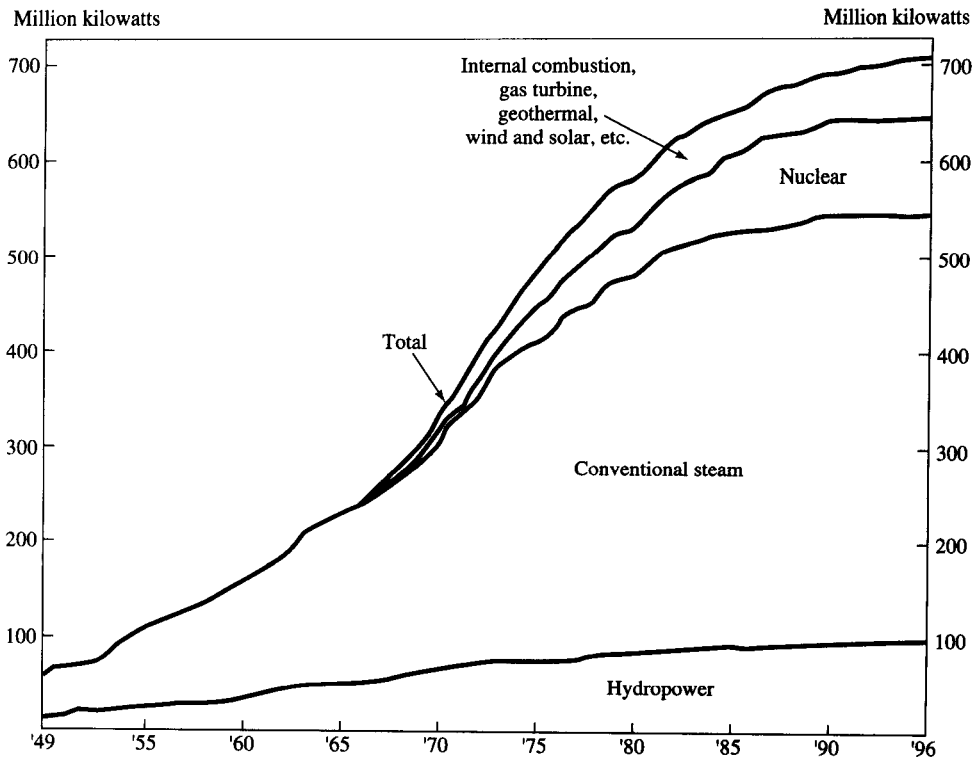


Figure 1.3 Electric utility generating capacity in the United States in the summer. (From *Annual Energy Review, 1996*, U.S. Department of Energy.)

In meeting the varying load requirements, economic considerations make it desirable to utilize plants fully with low (incremental) fuel costs while avoiding the use of plants with high fuel costs. This, in part, explains the use of nuclear plants for base-load service and gas turbines for peaking-power service; the different rates of utilization of these sources were noted earlier.

Finally, it is interesting to reduce the enormous numbers describing production and generating capability to human terms. In 1996 the U.S. population was

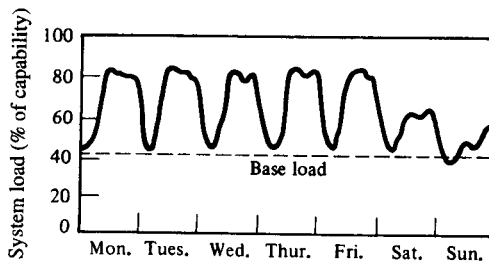


Figure 1.4 Daily load output (typical week).

approximately 265 million. Thus, there was a generating capability of approximately $710/265 = 2.68$ kW per person. Using the figure 0.49 for the capability (or load) factor, this translates into an average use of energy at the rate 1.3 kW per person. The latter figure is easy to remember and gives an appreciation of the rate of electricity consumption in the United States.

In the next few sections we consider some typical power plant sources of energy: fossil-fuel steam plants, nuclear plants, and hydroelectric plants. Space does not permit a detailed physical description. For more details, see a standard reference such as the *McGraw-Hill Encyclopedia of Energy*. The Web site www.powerlearn.ee.iastate.edu offers pictures of various items of power equipment. If you can arrange it, there is nothing better than a visit to a power plant.

1.2 FOSSIL-FUEL PLANT

In a fossil-fuel plant, coal, oil, or natural gas is burned in a furnace. The combustion produces hot water, which is converted to steam, and the steam drives a turbine, which is mechanically coupled to an electric generator. A schematic diagram of a typical coal-fired plant is shown in Figure 1.5. In brief, the operation of the plant is as follows: Coal is taken from storage and fed to a pulverizer (or mill), mixed with preheated air, and blown into the furnace, where it is burned.

The furnace contains a complex of tubes and drums, called a *boiler*, through which water is pumped; the temperature of the water rises in the process until the

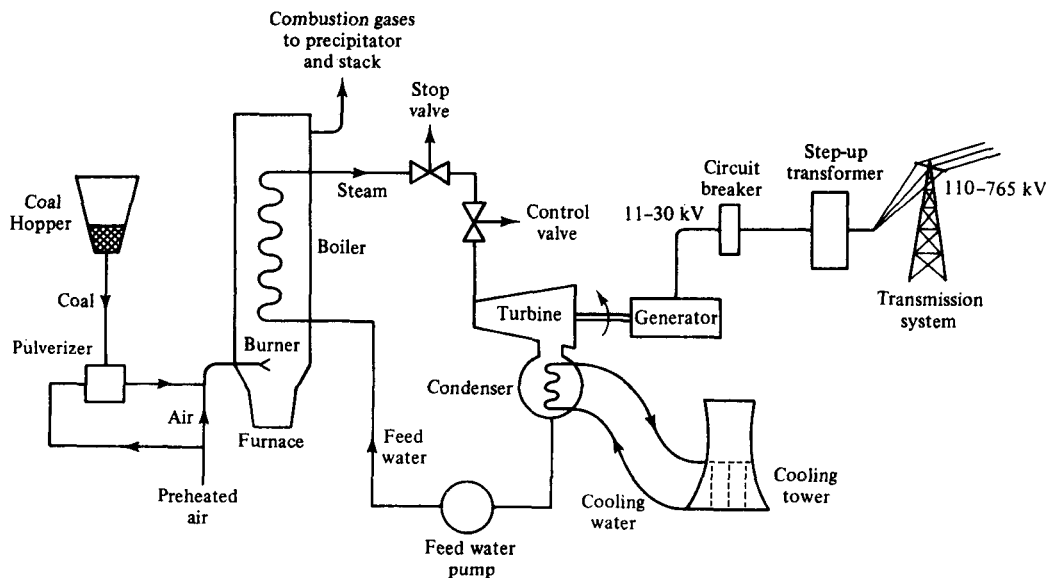


Figure 1.5 Coal-fired power station (schematic).

water evaporates into steam. The steam passes on to the turbine, while the combustion gases (flue gases) are passed through mechanical and electrostatic precipitators, which remove upward of 99% of the solid particles (ash) before being released to the chimney or stack.

The unit just described, with pulverized coal, air, and water as an input and steam as a useful output, is variously called a steam-generating unit, or furnace, or boiler. When the combustion process is under consideration, the term *furnace* is usually used, while the term *boiler* is more frequently used when the water-steam cycle is under consideration. The steam, at a typical pressure of 3500 psi and a temperature of 1050°F, is supplied through control and stop (shutoff) valves to the steam turbine. The control valve permits the output of the turbine-generator unit (or turbogenerator) to be varied by adjusting steam flow. The stop valve has a protective function; it is normally fully open but can be “tripped” shut to prevent overspeed of the turbine-generator unit if the electrical output drops suddenly (due to circuit-breaker action) and the control valve does not close.

Figure 1.5 suggests a single-stage turbine, but in practice a more complex multi-stage arrangement is used to achieve relatively high thermal efficiencies. A representative arrangement is shown in Figure 1.6. Here, four turbines are mechanically coupled in tandem and the steam cycle is complex. In rough outline, high-pressure steam from the boiler (superheater) enters the high-pressure (HP) turbine. Upon leaving the HP turbine, the steam is returned to a section of the boiler (reheater) and then directed to the intermediate-pressure (IP) turbine. Leaving the IP turbine, steam (at lower pressure and much expanded) is directed to the two low-pressure (LP) turbines. The exhaust steam from the LP turbines is cooled in a heat exchanger called a *condenser* and, as feedwater, is reheated (with steam extracted from the turbines) and pumped back to the boiler.

Finally, we get to the electric generator itself. The turbine turns the rotor of the electric generator in whose stator are embedded three (phase) windings. In the process mechanical power from the turbine drive is converted to three-phase alternating current at voltages in the range from 11 to 30 kV line to line at a frequency of 60 Hz in the United States. The voltage is usually “stepped up” by transformers for efficient transmission to remote load centers.

A generator (also called an *alternator* or *synchronous generator*) is shown in longitudinal cross section in Figure 1.7; the transverse cross section is approximately round. The rotor is called round or cylindrical or smooth. We note that steam-driven turbine generators are usually two pole or four pole, turning at 3600 rpm or 1800 rpm, respectively, corresponding to 60 Hz. The high speeds are needed to achieve high steam turbine efficiencies. At these rotation rates, high centrifugal forces limit rotor diameters to about 3.5 ft for two-pole and 7 ft for four-pole machines.

The average power ratings of the turbine-generator units we have been describing have been increasing, since the 1960s, from about 300 MW to about 600 MW, with maximum sizes up to about 1300 MW. Increased ratings are accompanied by increased rotor and stator size, and with rotor diameters limited by centrifugal forces, the rotor lengths have been increasing. Thus, in the larger sizes, the rotor lengths